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A virtual design studio for low frequency impact sound from walking

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Abstract – Experience with wooden multi-storey houses have shown that impact sound insulation is one of most critical issues to ensure a good indoor environment. Even in cases where the impact sound insulation is fulfilled, people perceive the sound from e.g. walking neighbours as very disturbing. To investigate the subjective perception, a test facility is needed which allows for a coherent evaluation of different floor designs by listening test. The facility should ensure, that when comparing different floors, the same excitation by a walker and the same receiving room are involved. Only the floor design should be changed. As a consequence the spread in the data will only be due to the spread in the perception by subjects. In this paper a virtual design tool for low frequency impact sound insulation is presented, which consists of four parts; measured walking forces, floor models, an auralisation system which consists of a grid of loudspeakers simulating the vibration of the floor and a receiving room furnished as a common living room. In a pilot study a listening test is carried out for 13 different floors with different impact sound spectra at frequencies below 100 Hz. The results indicate that the judged annoyance strongly correlates with the judged loudness. However, there is a substantial spread observed in between the subjects participating in the listening tests. To understand this spread, a more extended study is needed with more participants and a classification of the subjects with respect to criteria such as noise sensitivity or age.

Keywords: Impact sound insulation, Wooden floors, Subjective perception, Virtual lab environment

1 Introduction

Regulations and building codes have been established over the past decades to protect people from the negative impacts of a dysfunctional acoustic environment on health, wellbeing or cognitive performance. In common for most of the regulations is that they are expressed in terms of time-averaged energy-related measures such as sound pressure levels or reduction indices of walls. At the same time, over the years we have realized the importance of the information content of sound for the human response. The conscious or unconscious interpretation of sound by our brains strongly affects the level of annoyance or stress as well as our cognitive performance to an extent that we can even be struggling with our daily tasks. One dominant source of disturbing sounds in our homes is walking by neighbours, especially in wooden multi-storey buildings [1]. Residents of these buildings can be considerably disturbed by low frequency impact noise even though the buildings fulfil acoustic requirements according to regulation [2]. A common conclusion from the Swedish project Akulite is that this is mainly due to the strong low frequency response of the wooden floors [3]. As a result, in Sweden the frequency range for the impact sound measurements and ratings according to standards [4, 5] were extended down to 20 Hz, and a spectrum adaptation curve with weights on the third octave bands below 50 Hz were introduced. This improved the correlation between measurements according to the standard and the perceptual evaluation. However, the study was based on a relatively small sample of floors and a limited number of subjects [6, 8]. A comprehensive field study based on questionnaires can be found in [8]. There listening tests with recorded sounds are presented for different excitation. The results underline the difference between concrete floors and wooden floors with respect to annoyance.

To ensure a coherent subjective evaluation of impact sound from walkers on wooden floors is a rather complex task having in mind the different parts influencing the resulting sound pressure. The sound pressure signal $p(\mathbf{x_r}, t)$ measured in a room at position $\mathbf{x_r}$ depends on:

- the exciting force $F(\mathbf{x_e}(t), t)$ at the time varying position $\mathbf{x_e}(t)$ due to a walker which is strongly influenced by the individual walking style of a person and of course on the type of footwear, but also by the interaction between walker and floor,
- the response of the floor $H_{\text{floor}}(\mathbf{x_e}(t), \mathbf{x}, t)$ at position $\mathbf{x}$ due to a force varying in time and position.

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- and the response of the room $H_{\mathrm{room}}(\mathbf{x_r}, t)$ coupled to the vibrating floor. The room response will depend on room dimensions and damping due to wall absorption and furniture. This might also be influenced by flanking transmission depending on the overall building design.

The question concerning the walking forces is rather complex. In a previous study [9], the authors measured walking forces on two wooden floor structures with different density and stiffness. The force spectra of the two floors did not show any significant difference that could be connected to the floor properties despite smaller differences at the resonance frequencies of the floors. However when using these forces for auralisation (see [10]) it turned out that the resonances of the lightweight floors, especially the very first, influenced the resulting walking forces to such a degree, that they became audible – although very week – in the resulting auralized walking sounds. This means that assuming the walking forces as ideal force sources as done in this paper only can be considered as and approximation. In order to be able to use measured walking forces for the excitation of different floor models, the effect of resonances in the measured forces has been eliminated by using a curve smoothing technique [10].

The question of modal alignment between floor and room is a consequence of the low modal density at low frequencies. Air-borne sound and impact sound insulation are always case specific at low frequencies. The methodology presented here allows to select the degree of alignment in a controlled way. In this paper the room and floor size are corresponding to typical dimensions in field and a variation was not made in order to keep the duration of the listening test acceptable for the subjects.

To implement the approach a specialised listening lab for low frequency impact sound has been built as described in Section 2.1. The measured walking forces are used to excite the floor model are presented in Section 2.2. As model for the floor a simple orthotropic plate model with pre-stress is used as shown in Section 2.3. As a last step, the resulting surface velocity of the floor is mapped to the loudspeaker grid (see Sect. 2.4). The validation of the approach is carried out in two ways. Firstly, the different parts of the approach are validated separately by different means as presented in Section 3. Secondly, in the listening test presented in Section 4.1 the subjects were asked to judge the naturalness of the sounds. In Section 4.1 the virtual design studio is demonstrated by a listening test where ten different virtual floors and three versions of an existing floor are investigated.

2 Creating a virtual design studio for low frequency impact sound from walking

This section presents the different parts of the design studio consisting of the living room lab, the force excitation, the floor model and the procedure to map floor volume velocity due to floor vibrations to the loudspeaker grid.

Figure 1. The living room lab at Chalmers, Applied Acoustics.

2.1 The living room lab

The listening room was supposed to resemble a typical living room (see Fig. 1). The room (length: 4.8 m, width: 3.73 m, height: 3.6 m) is a room in a room design where the outer room (the receiving room of a former sound transmission lab) is placed on vibration isolators with a resonance frequency of about 4 Hz. The wall design of the inner room is a double wall design consisting of three layers of gypsum boards on separate studs. The air gap in between (150 mm) is filled with mineral wool. In the ceiling of the room a loudspeaker array is mounted consisting of twenty Genelec 8020B loudspeakers (mounted on a regular grid all over the ceiling) covering the mid and high frequency range between 66 Hz and 21 kHz and four Neumann KH805 active subwoofers (mounted in the four upper corners of the room) with a frequency range of 18–300 Hz. An Orion32 sound card is used to control these 24 loudspeakers. The suspended ceiling is installed at the height of 2.46 m from the floor, which makes the visible height of the room smaller than its actual height, and closer to the ceiling height of common apartments in Sweden. The ceiling tiles of the suspended ceiling are made of a thin woven cotton fabric with a weight per unit area of 0.265 $\mathrm{kg/m^2}$, which can be assumed as acoustically transparent at the low frequencies of interest in our experiments. The subwoofers are mounted close to the ceiling of the lab, near the corners, with the diaphragm centre approximately 36 cm away from the ceiling. The mid-to-high frequency range loudspeakers are installed 80 cm below the ceiling. This position might not be optimal from an acoustic point of view due to the relatively large distance to the reflecting ceiling. At higher frequencies it might lead to constructive or destructive interference between loudspeaker and image sources. However, Section 3 shows that this is not a critical issue for the sounds investigated here. The mid-to-high frequency range loudspeakers are mainly important for localization of the source position, i.e. where the walkers or other sources moves over time.

2.2 Measured walking forces

The excitation of the floor is based on measured walking forces. In literature, several measurement techniques are suggested to determine the ground reaction forces generated by the foot during walking, also known as stance forces or walking forces. The majority of these measurement techniques are based on direct measurement of forces induced by footsteps and require the test subject to walk on a surface other than a real floor. The surface can be for example an instrumented treadmill equipped with force plates [11, 12] or a fixed force plate [13, 14] that the walker needs to take only one step on. In some cases, in order to give more freedom to the walker to choose the walking path, the walker has to wear special shoes that have force transducers attached underneath [15, 16]. However, all these methods might manipulate the natural walking by imposing limitations on for example the number and direction of steps, the walking pace, the walking surface and the type of footwear. Thus, it is very likely that the data obtained from these measurements cannot be applied as a general solution for investigating walking forces generated by walking on real floors with or without footwear. To obtain accurate and realistic walking force data under natural walking conditions an indirect measurement method is used to measure stance forces on the floor. The method is based on the Least Mean Square (LMS) algorithm. The details of the applied method are described in [9, 17]. Different footwear as well as the case of barefoot walking are considered on a wooden joist floor. A typical result is shown in Figure 2.

The essential energy exciting the floor to vibrations radiated as sound is "hidden" in the sudden increase of the force at around 0.03 s, when the heel hits the floor surface. The small fluctuations visible over time turned out to be due to the feedback by the vibrating floor on the stance force. The main frequency of these fluctuations coincides with the first resonance frequency of the floor. As these fluctuations turned out to be audible in the simulations, it was important to remove them from the measured force records. Although they were very weak, they appeared as ringing in the auralised sounds and disturbed the overall impression. Just low pass filtering was no option as it would have taken energy from the sudden increase of the force due to the contact of the heel with the floor. Therefore a curve smoothing technique was applied to remove these fluctuations [10].

The tangential components of the forces are not taken into account in this approach because of their significantly lower amplitudes compared with the vertical forces [18], and thus their less influential effect on the walking sound in the flat underneath. For the excitation of the floor the forces for the barefoot walker are used as they create most dominant low frequency sound. To create realistic scenes some properties for the virtual walker have to be defined. Whenever the walker strode along a straight line (see Fig. 3), a 10 cm gait base, also known as the stride width (the lateral distance between the mid-lines of the two feet during walking), is used. In consecutive steps, the step length that is applied in the model, is 60 cm. The heel and ball forces are replaced by a single point force. This has been proved to be reasonable at these low frequencies. Results for one single point force and two separated point forces did not show any differences [10]. Therefore, the gait

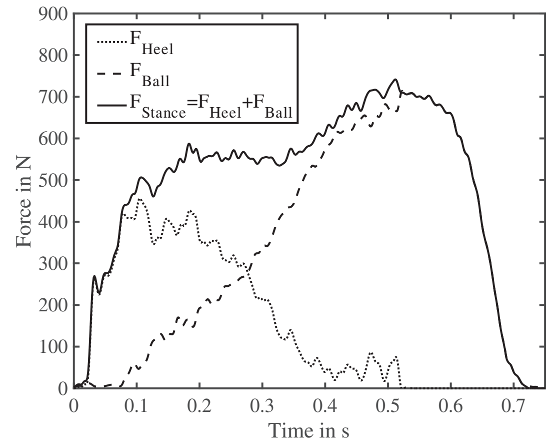

Figure 2. Example of measured stance force for barefoot walking.

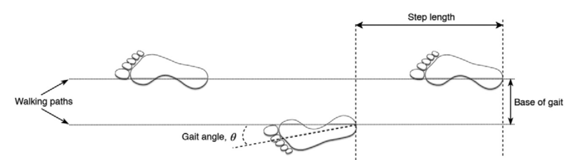

Figure 3. Walking path parameters.

angle θ between the axis of the foot and direction of walking was not of any interest in the model.

For the simulation of a walker, a sequence of steps is defined following different paths on the floor as shown in Figure 4.

During initial listening tests it turned out that the walking sound was too repetitive, as only a limited number of steps were available. Therefore, a piece-wise randomisation of timing and amplitude of different phases of stance forces were introduced. Up to 20% variation in the signal length and 10% in the amplitude are applied to create a variability to increase the plausibility of the walking sounds. The resulting sequence of forces is shown in Figure 5.

The time record of the walking forces at the different positions are transformed to the frequency domain and will be applied as excitation forces in the floor model.

2.3 A simplified floor model

The model for calculating vibrations of a floor due to walking forces is rather simple and follows classical text book examples. The simplicity is however no limitations as more complex floor designs could easily be modelled by Finite Elements and included in the same way if needed. The focus was demonstrate the methodology of the approach by using bare floors. To add floating floors or suspended ceilings mighty be very interesting but might also blur the picture.

Therefore for simplicity reasons thin rectangular simply supported plates are assumed with mode shapes ϕ_n of the form,

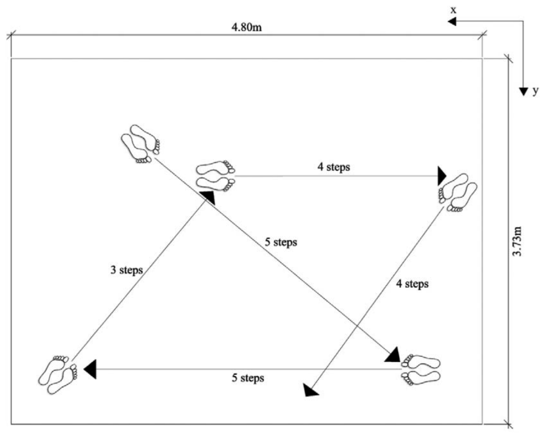

Figure 4. Walking path of the virtual walker.

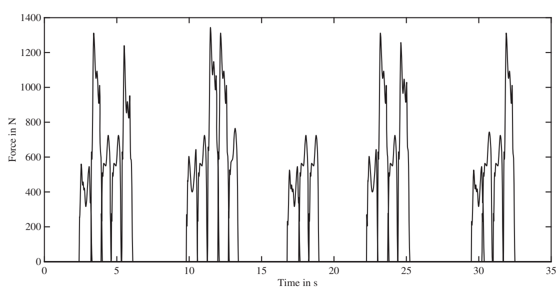

Figure 5. Walking forces created by the virtual walker after randomisation of timing and amplitude.

$$\phi_n(x,y) = \sin\left(\frac{n_1 \pi x}{l_x}\right)\sin\left(\frac{n_2 \pi y}{l_y}\right), \tag{1}$$

where l_x and l_y are the length and width of the plate and n_1 and n_2 are the number of half wavelengths fitting to the width and length. In the calculations n_1 and n_2, were 30 and 40, respectively.

As we use thin plates we can apply a simple Kirchhoff plate model, however as we allow the plate to be orthotropic and being exposed to a pre-stress the extended homogenous wave equation looks as follows:

$$B_x \frac{\partial^4 \phi_n(x,y)}{\partial x^4} + B_y \frac{\partial^4 \phi_n(x,y)}{\partial^4 y^4} + B_{xy} \frac{\partial^4 \phi_n(x,y)}{\partial x^2 \partial y^2} + T_x \frac{\partial^2 \phi_n(x,y)}{\partial x^2} + T_y \frac{\partial^2 \phi_n(x,y)}{\partial y^2} - m'' \omega^2 = 0, \tag{2}$$

where B_x and B_y are the bending stiffnesses in x and y direction and B_{xy} is the mixed bending stiffness. The bending stiffness' B_x and B_y are calculated as $B_x = E_x h^3/(12(1-v^2))$ and $B_y = E_y h^3/(12(1-v^2))$. E_x and E_y are the Young's moduli in x and y direction and v is Poisson number. The mass per unit area m'' is the material density ρ multiplied with the thickness h of the floor. The cross stiffness B_{xy} is approximated as the geometrical average $B_{xy} = \sqrt{B_x B_y}$. T_x and T_y are the pre-stress in x and y direction. ω is the angular frequency assuming a harmonic motion of the form $e^{j\omega t}$. From Equations (1) and (2) the eigenfrequencies can be derived as,

$$\omega_n = \sqrt{\frac{B_x}{m''}}\left(\frac{n_1\pi}{l_x}\right)^2 + \sqrt{\frac{B_y}{m''}}\left(\frac{n_2\pi}{l_y}\right)^2 + \sqrt{\frac{B_{xy}}{m''}}\left(\frac{n_1\pi}{l_x}\right)\left(\frac{n_2\pi}{l_y}\right) + \sqrt{\frac{T_x}{m''}}\left(\frac{n_1\pi}{l_x}\right) + \sqrt{\frac{T_y}{m''}}\left(\frac{n_2\pi}{l_y}\right). \tag{3}$$

As a last step it is only needed to expand the walking forces into modal forces before the usual approach for a modal superposition is carried out. The resulting velocity field is used to calculate the required volume velocity to be produced by the loudspeaker system in the ceiling.

2.4 Mapping the calculated floor volume velocity to the to the loudspeaker grid

To auralize the walking sound, the calculated surface velocity is mapped to the loudspeaker grid in a way that the volume velocity produced by the loudspeaker system approximates the spatial distribution of the volume velocity created by the floor vibrations.

For this, 20 mid-to-high frequency range loudspeakers and 4 subwoofers, mounted in the ceiling of the lab, were used. The mid-to-high frequency range loudspeaker grid is shown in Figure 6. For the subwoofers the area is just divided into four equal parts.

For a grid area S_i, the volume velocity Q_i created by the floor is calculated by integrating the velocity v_{ij} over this area. The integration is carried out as sum over small discrete elements ΔS_j inside S_i,

$$Q_i = \sum_{j=1}^{J} v_{ij} \Delta S_j. \tag{4}$$

By dividing the total volume velocity Q_i by the area of the diaphragm, $S_{\text{diaphragm},i}$, belonging to the corresponding loudspeaker, the required membrane velocity is obtained.

A digital crossover filter is used to separate the low frequencies from the high frequencies. Tailor-made hamming filters were applied for this purpose. The velocity signals for subwoofers were low-pass filtered at a cut-off frequency of 70 Hz, and the mid-to-high frequency range loudspeaker signals were high-pass filtered at 70 Hz. To obtain the correct equivalent loudspeaker velocity, $v_i = Q_i/S_{\text{diaphragm},i}$, one needs to compensate for the internal transfer function of the loudspeaker. In order to do this, the transfer function between the input voltage and the vibrations of the membrane of the diaphragm has been measured for both types of loudspeakers. The velocities were measured using a laser doppler vibrometer. The inverse filter has been calculated using the LMS algorithm as described e.g. in [19]. As all loudspeakers are ported, an attempt was made to correct for the port velocity. Details can be found in [10]. However, later-on it turned out that we only partly succeeded with this attempt (see Sect. 3).

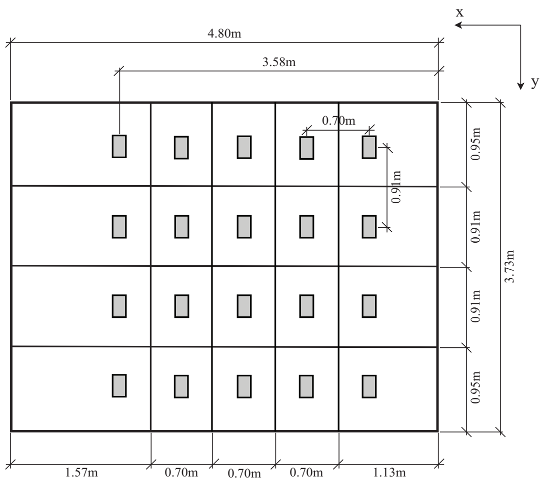

Figure 6. Positions of the mid-to-high frequency range loudspeakers.

The described procedure establishes a connection between the simulated velocities of the floor and the required voltage signals at the loudspeakers. With this it is possible to auralise the vibrating floor when a person walks on it. The auralisation will work at any position in the listening room and will also include the possibility to localise the position of the walker over time.

3 Validation of the design studio for low frequency impact sound from walking

The aim of the design studio is to create an environment that allows for providing stimuli to the listeners as expected from impact sound from real floors and capturing the differences between different floor designs correctly.

For this, one has to ensure that:

- the whole chain for the auralisation is implemented correctly,
- the changes in the floor design are reproduced in an adequate way, and
- the listener experiences the sound as plausible.

Answering to these questions is not a simple task. The quality/plausibility of the auralised signals depends on the quality of the measured walking forces, the floor model and the auralisation procedure as described in the previous section.

The walking forces are based on measured forces. Amplitude, timing and frequency content correspond well with what is found in [20]. For the purpose to study the subjective perception of different floor designs it might be sufficient that the forces are reasonable and are kept identical from floor to floor.

The floor model is a very simplified model and might not capture the complexity of real floors. To ensure that models are working properly the calculated mobilities were compared with the mobilities of the corresponding infinite structure. In addition, plausibility checks were carried out ensuring the correct influence of different physical parameters on the vibration results (see also [10]).

The critical step in the auralisation procedure, however, is the link between floor velocities and sound pressure signals in the living room lab. It is important to ensure that the approach to map the floor volume velocity due to floor vibrations on the loudspeaker grid is correct and able to auralise the differences between different floor designs correctly. For this, the auralisation signals were measured in the living room lab in the position of the listener. These signals are referred to as "recordings" in the further text. For validation, a room model has been implemented based on a modal approach. The model only represents an empty room with the dimensions of the living room lab. The damping of the room, modelled as complex eigenfrequencies has been roughly adapted to the reverberation time measured in the living room lab. In the model the vibration pattern on the floor due to a walker is given as source layer on the ceiling of the room model. Eigenfrequencies of the room up to three times the highest frequency of interest are considered. The frequency resolution in the simulation is 0.08 Hz. This complete analytical model also provides signals for the sound pressure in the listening position (referred to as "simulations" in the further text) which can be compared with the recorded signals.

The floors used for the validation are representatives of the four different floor classes in the listening test. Floor M1 represents a typical cross laminated timber (CLT) floor, M4 is a pre-stressed version of M1, M9 represents an isotropic wooden floor and M10 a light concrete floor. More detailed descriptions of the floors can be found in Section 4.1 in Table 1.

A critical element in the auralisation is that the loudspeaker grid is supposed to represent a vibrating ceiling situated directly above the acoustically transparent suspended ceiling in the height of 2.64 m. However, the loudspeaker grid is mounted at 2.8 m (middle and high frequency range loudspeakers) and the fours subwoofers are mounted below the ceiling of the lab at the height of 3.26 m. The question arises if the positioning will really give results as the ceiling would be at 2.8 m just above the suspended ceiling. Therefore three different scenarios are compared:

- Case 1: a room of height 3.6 m with the ceiling placed on 2.8 m.
- Case 2: a room of height 3.6 m with the ceiling placed on 3.6 m.
- Case 3: a room with height of 2.8 m with the ceiling placed on 2.8 m.

The results from the simulations show that the positioning of the vibrating ceiling as well as the room height has very little influence on the sound pressure levels in the position of the listeners at these low frequencies (see Fig. 7). While case 1 and case 2 hardly show a difference, case 3 gives slightly higher sound pressure levels due to the reduced volume of the room.

Table 1. Material parameters of the 10 simulated floors used in the listening test.

Floor	ρ	ν	E_x	E_y	T_x	η_{int}
	kg/m^3		GPa	GPa	kN/m	
M1	450	0.35	10	0.37	–	0.2
M2	450	0.35	7.5	0.37	–	0.2
M3	450	0.35	5	0.37	–	0.2
M4	450	0.35	10	0.37	5000	0.2
M5	350	0.35	10	0.37	–	0.2
M6	250	0.35	10	0.37	–	0.2
M7	450	0.35	10	0.37	–	0.3
M8	450	0.35	10	0.37	–	0.1
M9	450	0.35	10	10	–	0.2
M10	1600	0.2	14	14	–	0.07

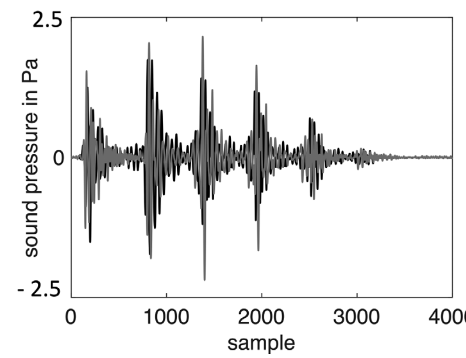

Figure 8. Time signal of the pressure signal at the listener position for the first five steps for the simulation (black line) and the recording (gray laine) on floor M10.

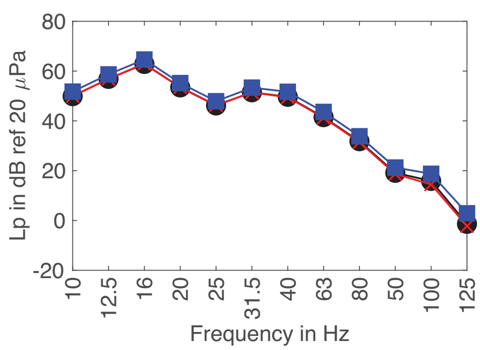

Figure 7. Simulated sound pressure levels for a light concrete floor (M10) for three different room configurations; case 1: circles, case 2: crosses, case 3: squares.

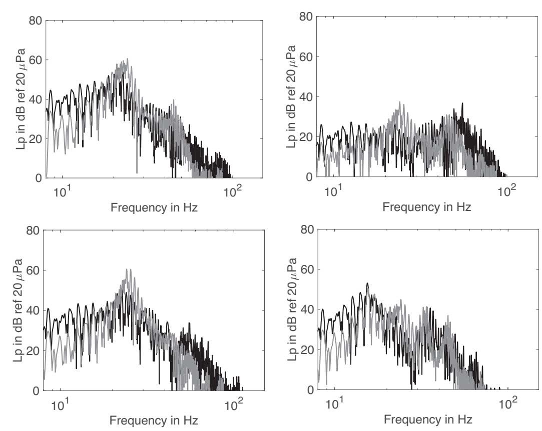

Figure 9. Comparison between the room model (black) and the recording in the living room lab (light gray) for the floors M1 (left upper corner), M4 (right upper corner), M9 (left lower corner) and M10 (right lower corner). Narrow band spectrum with $\Delta f = 0.03$ Hz.

This means that for the auralisation the mounting position of the loudspeakers between the real ceiling and the acoustic transparent ceiling is sufficient.

The second question to be answered is whether the mapping of the floor volume velocity due to floor vibrations on the loudspeaker grid is working correctly.

Figure 8 shows an example of the recorded and the simulated time signals in the listener position for the first five steps of the walking path described in Section 2.2.

The amplitude and timing of the pressure signal show a good agreement although the recording shows slightly higher peak values and a bit more damping. One has to have in mind that the recordings are made in a room with furniture while the simulations are carried out for an empty room.

Figure 9 shows the narrow band spectra for the recordings and the simulations for the four floors mentioned before in this section. Due to periodicity of the footsteps, the spectra become like line spectra. In general, for all four floors, the frequency contents in recording and simulations are very similar. At very low frequencies, the simulation delivers generally higher levels due to the frequency characteristics of the subwoofers at frequencies below 15 Hz, which has not been compensated completely. In addition, in all recordings, there are somewhat higher levels observed around 25 Hz in comparison to the simulation. This indicates that we did not manage to compensate completely for the contribution of the subwoofer port.

This, however, is not a severe drawback as the influence of the somewhat too high response of the subwoofers will be the same for all floors. One could consider this an additional system property of the living room lab in the same way as the resonances of the room. The important fact is that the somewhat increased response is not visible when comparing the influence of the different floor designs. For this comparison, floor M1 is used as reference. The level difference ΔL for Floor number Mn is calculated as,

$$\Delta L = L_{Mn} - L_{M1}, \tag{5}$$

in the third octave band spectra. This is done for recording and simulations. The results are shown in Figure 10.

The results underline that recording and simulation reproduce the same dependency on floor design at least at very low frequencies. At higher frequencies some differences can be observed. At the same time, the main response of the floors are at low frequencies.

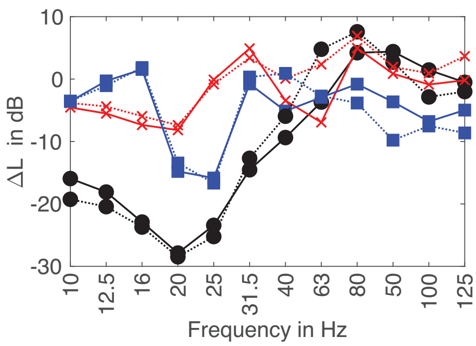

Figure 10. Level differences for recordings (dashed lines) and simulations (solid lines) for floor M4 (circles), floor M9 (crosses) and floor M10 (squares). Reference is floor M1.

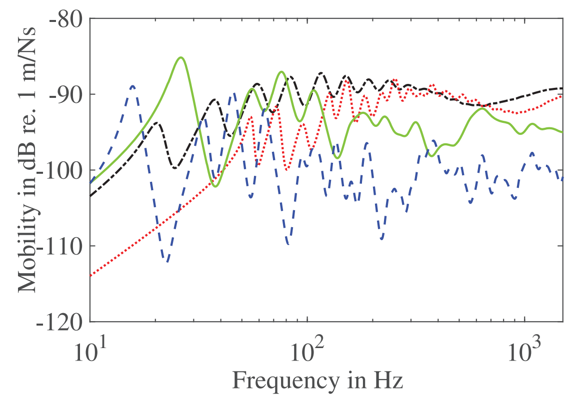

Figure 11. Driving point mobility calculated as $20\log_{10}$ ($|Y|/|Y_{\mathrm{ref}}|$) with Y_{ref} = 1 m/Ns for $M1$ (-.-), M4 (...), M9 (—), and M10 (–).

One can summarise that the comparison between the recordings and simulations reveal that the whole chain for the auralisation is implemented correctly, and that the changes in the floor design are reproduced in an adequate way. The most important part, however, is that the results shows that the mapping of the floor volume velocity due to floor vibrations to the loudspeaker grid works well. The loudspeakers create sound fields which are comparable with the simulations, where a continuous velocity distribution is used.

The question whether the auralised signals are perceived as plausible will be investigated in the listening test in the following section.

4 Demonstration of the virtual design studio for low frequency sound from walkers

In the following, the potential of the virtual design studio for low frequency sound from walkers is demonstrated. Different floor designs are auralised and presented to listeners for a subjective evaluation. Section 4.1 presents the different floor designs. The listening test as described in 4.2 has more the character of a pilot study than of a complete study on the subjective perception of walking sounds. Despite this the results of the listening test presented and discussed in Section 4.3 give some insight into the complexity of the question.

4.1 Parameters of the floors used in the listening tests

Ten different floors have been implemented in the model described in Section 2.3. The material properties of the floors are presented in Table 1. All floors have a thickness of 0.1 m. The material properties of the orthotropic floor M1 are chosen based on the properties provided for a typical CLT floor in the literature, e.g. in [21]. The damping values also include the loss due to adjacent building partitions. For M10, properties of lightweight concrete, given in e.g. [22], are used. It should be pointed out that the material properties of all floors were selected in a way that the resulting walking sounds become audible and clear, which corresponds to a poor impact sound insulation performance. However, the aim of this study is not to suggest a good floor design, but to demonstrate and investigate the capabilities of the design tool. In addition to the model floors, floor vibrations measured in field were used for auralisation. The floor vibrations from this measurement were used in three versions; the original version, and two versions where the vibration levels are reduced by 6 and 9 dB. This means that in total 13 different stimuli are provided to the subjects. Figure 11 exemplifies the three main categories of floors used in the listening test.

Floor M1 represents the group of orthotropic wooden floors. Its first resonance frequency is at around 20 Hz and it shows a relatively high mobility due to its low weight. M4 is the only floor with pre-stress in the x direction. The pre-stress moves the first resonance frequency to above 50 Hz. M9 is an isotropic wooden floor. In total it is stiffer and the first two resonance frequencies are very close to each other which explains the strong response at around 26 Hz. M10 is a relatively thin concrete floor. Due to the higher mass per unit area, the first resonance appears already at 17 Hz and the mobility is in general lower. The size of the floors corresponds to the ceiling of the listening room (i.e. a length of 4.8 m and a width of 3.73 m). The mobility was either calculated (floor M1–M10) or measured (M11) in the position (x, y) = (0.8 m, 0.3 m). The floors M11 and its attenuated versions M12 and M13 were added to provide a real floor example to investigate if there is a difference in plausibility judgement between the auralisation based on the floor model and based on field measurements. Floor M11 was a wooden joist floor installed in a two-storey test house at RISE Research Institutes of Sweden. It belongs to a single-family (test) house, for which there is no strict sound insulation regulation, which means that the floor is built without considering acoustic performance, and the impact sound insulation was relatively poor. The floor had the dimensions $L \times W$ = 4.74 m × 3.73 m, which is very similar to the dimensions of the ceiling in the listening lab. The total thickness of the floor structure was 327 mm. The bare floor consisted of 22 mm thick chipboards screwed to the floor joists, which had the cross-section dimension of

45 mm × 220 mm and were spaced 600 mm apart. Wooden parquets were used as floor covering and underneath them a 30 mm layer of plastic foam was installed that held the floor heating pipes. A 45 mm layer of isolating material was placed on furring strips with the dimensions of 28 mm × 70 mm screwed 300 mm apart under the floor joists. A plastic foil was placed between the joists and the furring strips to stop the mineral wool from falling. For the ceiling, 13 mm gypsum boards were used. For the vibration measurements, twenty accelerometers were mounted on the ceiling of the receiving room. Considering the similar dimensions of the test floor to the ceiling of the listening lab, the accelerometers were attached at the same positions underneath the floor as the center point of the loudspeakers in the listening lab. The sensors recorded vibrations when a person walked on the floor using the same walking paths as illustrated in Figure 4. The walker was the same person whose walking force signals were measured and used in the simulations. For reproduction of the walking sound from the measurements, first, velocity signals at the measurement positions were calculated by time-integrating the measured accelerations. Velocities at all node points in the floor mesh, as defined in the simulations, were then calculated by a two-dimensional linear interpolation of the measured velocity signals. This was made for a more accurate calculation of the total volume velocity of the floor areas represented by the loudspeakers. After calculating the node velocities for the entire floor, the same procedures for calculating equivalent loudspeaker membrane velocities and the auralization chain, as for the simulations were used to obtain the output signals for the loudspeakers. The impact sound pressure levels for all floors were measured and evaluated on the basis of the ISO 16283-2 and ISO 717-2 standards (see Tab. 2). For the floors M1 to M10 this was done by first exciting the floors with a virtual tapping machine and calculating the floor vibrations due to the hammer impacts. The forces of the virtual tapping machine only contained frequencies up to 1600 Hz due to the limitation in the measurement equipment when applying the force identification approach presented in [9]. Consequenctly also the the auralisation was limited in frequency. However, for the type of floors we investigated, the frequencies above 1600 Hz are not expected to contribute to the weighted standardized impact sound pressure levels. The approach should in any case be considered rather as an attempt to compare the floors than to deliver absolute correct values. The tapping machine sound was then auralized using the virtual design tool and the same procedure as for the walking sound. The resulting impact sound pressure levels in the listening lab were then measured and evaluated according to the ISO standards to obtain the single-number quantity of impact sound insulation of the floors. Six virtual tapping machine positions were used for each floor, and for each position a 30-second-long sequence of hammer impact forces was generated. The force data for the tapping machine were acquired from measurements and corresponded to a Norsonic type Nor-211A tapping machine. More details about the auralization of tapping machine and determination of impact sound insulation of model floors is presented in [10] and [23].

The impact sound insulation calculations for the floor M11 were done the same way as for the model floors, with the difference that the floor vibration data for M11 were obtained directly from measurements, using accelerometers attached to the ceiling of the receiving room, as explained earlier.

The auralised sound pressure levels in the listening lab were then measured and evaluated according to the ISO standards to obtain the single-number quantity of impact sound insulation of the floors. The weighted standardized impact sound pressure levels, $L'_{nT,w}$ for each floor was determined according to the procedure described in ISO 717-2. Furthermore, two spectrum adaptation terms $C_{I,50-2500}$ and $C_{I,20-2500}$ were calculated according to ISO 717-2 and the Swedish standard SS 25267:2015, respectively as developed to take into account the performance of mainly lightweight floors at low frequencies down to 50 Hz and 20 Hz. The results are shown in Table 2 as well. They will be later compared with results from the listening test.

4.2 The design of the listening test

For subjective evaluation of the walking sound on different floors semantic differentials [24] were used. The adjectives used in the semantic scales were selected in association with various properties of the sample floors. The semantic differentials were adapted so that they could reflect the intended physical properties of the floor and also gave information about the plausibility of the sounds. Therefore, both bipolar and artificial bipolar semantic scales were used in the test. For example, for evaluation of loudness a bipolar scale using the adjectives "Low" and "High" was used, while for example for annoyance, an artificial bipolar scale ranging between "Not annoying" and "Very annoying" was used. The rating scales consisted of 7 equidistant steps, ranging from 1 to 7. A list of the attributes as well as their range are presented in Table 3. Attributes such as distinctness and thumping have been used in the literature [25] to describe the perceived impression of impact sound from walking on different floor structures.

In the listening test, only footstep sounds generated by walking barefoot on a floor were used. The motivation is that barefoot walking has shown to have more audible low-frequency content and is perceived more annoying than the footstep sounds generated by walking with shoes [7]. The selected listener's sitting position was only representative of a real-life case, with the listener sitting on the sofa in front of the TV. This means that selection of the listening position was not based on the flatness of the room response in that position. The only consideration for the sitting position was to be away from the center and the corners of the room, where the probability of exposure to the minimum or the maximum sound pressure level in the room is higher. Twenty subjects (16 male, 4 female) participated in the experiment. Their age varied between 23 and 40 years with an average of 28.8 years. The majority of participants (17 out of 20) were students and staff at the Applied Acoustic division at Chalmers University of Technology.

Table 2. Weighted standardized impact sound pressure levels and correction terms in dB.

Floor	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
$L'_{nT,w}$	60	60	59	59	62	65	58	62	59	51	68
$L'_{nT,w} + C_{I,50-2500}$	71	73	72	72	74	77	70	73	70	67	72
$L'_{nT,w} + C_{I,20-2500}$	85	86	83	73	85	87	83	89	81	77	81

Table 3. List of attributes used in the listening test and their range.

Attribute	Range	
Loudness	Low	High
Distinctness	Not distinct	Very distinct
Thumping	Not thumping	Very thumping
Reverberation	Not reverberant	Very reverberant
Annoyance	Not annoying	Very annoying
Naturalness (plausibility)	Artificial	Natural

The subjects had different nationalities and were from 3 different continents (America, Europe and Asia) with a majority from Europe. Nearly half the test participants (9 out of 20) reported having lived in buildings with wooden floors, all of which were well familiar with hearing their neighbors upstairs walking, and 7 of them reported being regularly disturbed by the walking sound. The rest of the subjects reported having lived in buildings with concrete floors. Of these 11, 5 stated to have no experience of hearing impact sound from walking. In total, 7 subjects reported having been annoyed by the impact sound generated by walking at home, all of which lived in buildings with wooden floors. The listening test was performed with one participant at a time. The subjects were informed in advance about the procedure of the test and that they were going to evaluate walking sounds. They were also told that they are free to leave the room at any time and for any reason during the experiment or withdraw from the experiment if they wish. The results were anonymized before stored for later evaluations. The instructions of the test were presented in a written format. Also, the test leader attended the training session to answer questions. Before the start of a test, the subjects first evaluated three sounds, M5, M10 and M11, as training, in order to get familiar with the test procedure and the content of the sounds. The 13 test sounds, M1–M13, were then presented to the participants in an individually randomized order. Each sound sample was played twice, which means that each participant assessed 26 sound samples in total. The duration of each sound sample was 35 s, and they were played in a loop with the possibility for the participant to pause the sound if they wanted. No information about the loudness range was given to the participants in advance, because they were asked to judge the sounds based on their own perception of a real-life case at home. The tests lasted 40 minutes on average

4.3 Results from the listening test

Figure 12 summarizes the listening test results for all the participants and all the sound samples as boxplots.

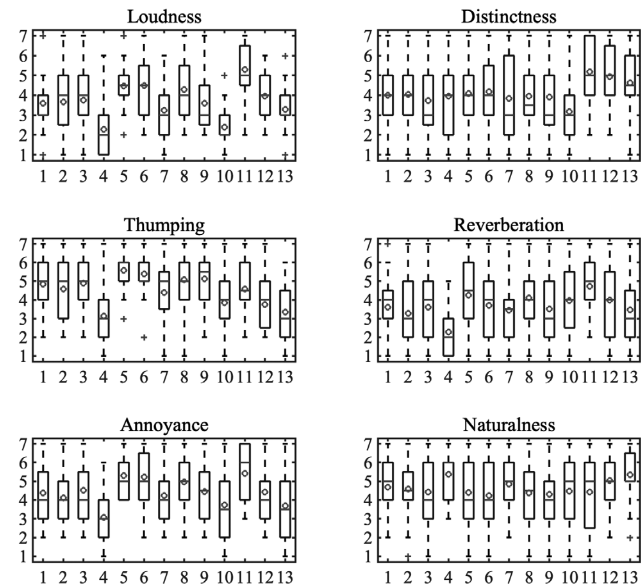

Figure 12. Listening test results for all the participants and all sound samples. The horizontal axis represents the floor sample, and the vertical axis shows the rating values. The circles show the mean values of the data for each sound sample in each category.

The horizontal line inside the boxes shows the median (50th percentile) value, and the lower and upper edges of the boxes show the 25th and 75th percentiles, respectively. The whiskers show the outmost ratings that fall in the lower and upper range of 1.5 times the interquartile range (1.5 IQR). Any rating outside the whiskers is shown as an outlier and is displayed as "+".

For almost all the sounds in all attribute categories, the subjective responses are spread over the entire rating range. However, depending on the attribute and the floor, the distribution of the answers differs. The data are analyzed using mean and regression analysis as well as a combination of one-way ANOVA and t-test analysis in order to investigate the statistical significance of the results.

Among the 6 categories, the perceived loudness shows the most variation for the different floors. Analysis of the loudness data shows that for every floor there are at least two other floors that are judged as significantly different in loudness. The judgements in the annoyance category appear to follow the same pattern as the loudness data implying that there is a correlation between these data, as expected. However, there are less variations in the perceived annoyance than in the loudness.

One of the main interests in this pilot study was to clarify how natural the walking sounds are experienced by

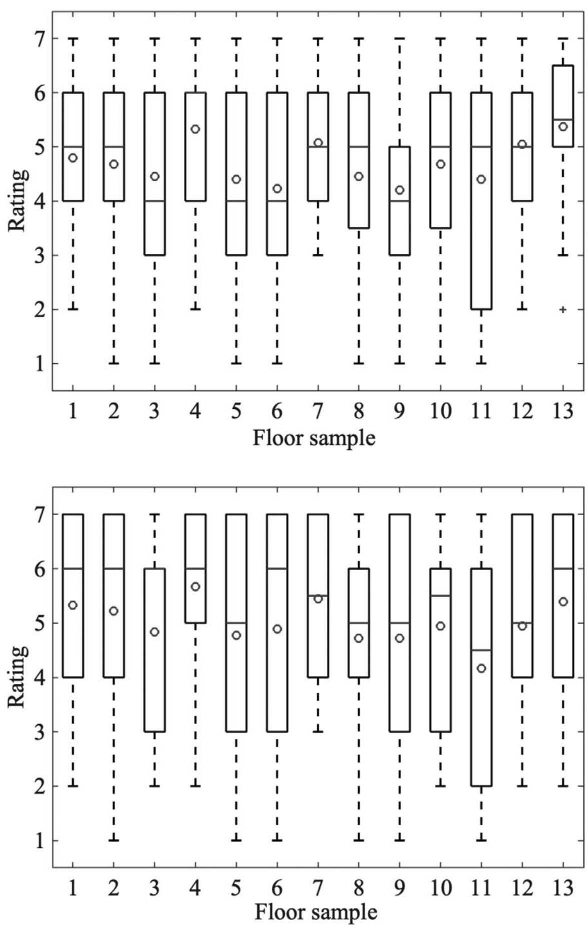

Figure 13. Assessment of naturalness of walking sound samples. The circles show the mean values of the data. The results from all subjects are shown in the upper figure while for only those who have experienced impact sound from wooden floors are shown in the lower figure.

the subjects, i.e. the plausibility of the auralized walking sounds. Due to the importance of naturalness ratings for evaluation of the virtual design tool, these data are presented separately in Figure 13 for further analysis. The boxplots in the upper figure show the data for all the participants, while the graph in the lower figure illustrates the naturalness judgements by those participants with experience of having lived in apartments with wooden floors.

The variations in ratings of the categories reverberation and thumping, which are connected to material properties of the floors, show that the changes in the floor design are reflected in the auralized sounds and have caused differences in perception of the walking sounds. For example floors M5 and M6 which have the lowest densities among the floor models, have the highest thumping ratings with high consensus among the test subjects. These floors are also perceived to have more reverberation compared with other model floors, but with a larger spread in the answers compared with thumping ratings. Moreover, for the pre-stressed floor, M4, there is high consensus among the test subjects about the low reverberation and low thumping of the walking sound. Another category which corresponds to the characteristic of the auralized walking sounds is distinctness, that was described for the test subjects as distinguishability and clarity of the successive footsteps. The ratings for this category do not show any significant variations, except for floor M10. Moreover, all boxplots in this category have long whiskers spreading almost along the entire rating range, which means that the test subjects did not have a consensus about the distinctness of the auralized walking sounds. This could be due to various reasons. It might imply that different subjects had different understanding regarding the meaning of distinctness. Some might have associated it with sharpness and translated distinctness as presence of higher frequencies. In that case it would become difficult to evaluate the given samples due to the dominance of frequencies as low as 20 Hz in the sounds. The rating of distinctness is expected to have improved and become more homogeneous if sounds from walking with shoes that contain higher frequencies were used instead of barefoot walking sounds. The results for all the participants show that the naturalness ratings have the minimum variations among the six categories, with no significant difference between any of the sound samples (used significance level is 0.01). The average naturalness ratings for all model floors are between 4.2 and 5.3 (out of 7), with no significant difference from the ratings for the three real floor samples. The real floors received an average rating between 4.4 and 5.3, which implies that the subjects, on average, could not distinguish the walking sounds generated using floor vibrations simulations from the sounds generated by using measurement data on a real floor. Moreover, the results show that the majority of the perceived naturalness ratings for all floors are above 3.5, which is the mean value of the rating range, with 75% of the ratings being 4 or more, 57% between 5 and 7 and 15% being 7. This means that the majority of the participants found the auralized sounds plausible.

The walking sounds with the lowest perceived loudness (M4, M7, M10 and M13) are perceived as the most natural or plausible sounds. This can be due to the fact that the floors that are used in real buildings are often designed with better impact sound insulation performance than the floor objects presented here. Therefore, those floors that with lower walking sounds might be more comparable with the real floors and thus, perceived as more natural. We also asked the test subjects about the experience to have lived in apartments with wooden floors. Among those with this experience, the naturalness of the sounds received higher ratings. The boxplots in Figure 13 (lower figure) present the data for this group only. The naturalness of the sounds is on average rated higher than when all subjects are included. The increased naturalness rating is more noticeable for all the model floors, and the average rating for these floors ranges from 4.7 to 5.7, while the maximum average rating for the real floor examples is 5.4 (M13). Moreover, 7 of the model floors have an upper quartile value of 7 for naturalness, which means that the simulated walking sounds have been perceived as completely natural by at least 25% of the experienced test subjects. Among the real floor examples, only the sample with −9 dB sound reduction is perceived as equally natural. Therefore, it can be concluded that the auralized walking sounds are perceived as plausible even or especially among the experienced test subjects.

The low naturalness rating for the real floor (M11) with actual measured velocity amplitudes can be correlated with its high loudness (mean = 5.4) and reverberation (mean = 4.8) ratings, which also result in high perceived annoyance (mean = 5.5) by the sound. So, when the sound is reduced by 6 and 9 dB, the perceived annoyance and reverberation were reduced, and the perceived naturalness increased accordingly. For the floor samples M12 and M13, respectively, 63% and 80% of the naturalness ratings are 5 or more.

Generally the naturalness or plausibility of the auralised sounds is not easy to judge and depends on the experience of the listener. It turned out that the subjects with experience of walking sounds from wooden floors judged the naturalness higher than those with experience from concrete floors or no experience at all. Also seen in later studies. Most of the floors are rather on the bad side with respect to impact sound insulation. This might also lead to a lower judgement of the naturalness. Quieter floors such as the floor M4 gave higher ratings.

In addition to the statistical data collected by the listening test, the subjects were asked whether they have any comments about the experiment. A comment, which was given by at least 7 participants about the naturalness of the sounds, was that some of the sound samples resulted in a rattling sound, probably generated by vibrations of a floor lamp, that made the total experience more plausible. One of the subjects associated the sound with rattling of dishes in the kitchen cupboards, which by that subject was perceived close to reality. Investigating this effect was not possible in the time frame of this work.

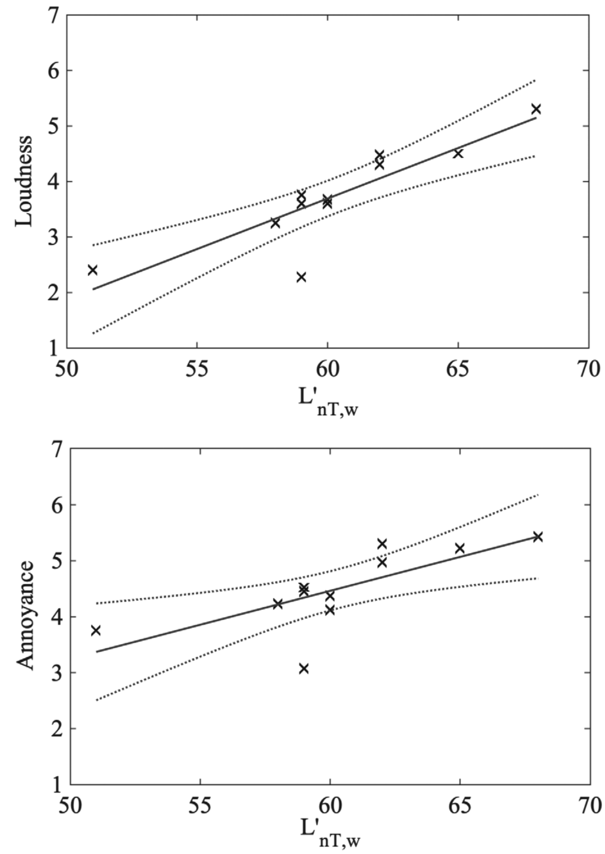

Figure 14. Relationship between impact sound insulation rating of the floors and the subjective loudness and annoyance of walking sounds.

4.4 Comparison of the results from the listening test with the impact sound insulation rating

The floor models with low density (M5 and M6) and the model with low damping (M8) as well as the real floor (M11) are perceived to have the most annoying walking sounds with the majority of the ratings being 5 or more (70% for M5, 68% for M6, 60% for M8 and 75% for M11). Also, these sounds have on average higher ratings for perceived loudness with a mean value above 4.4. The subjective evaluation results for these floors are in agreement with the impact sound insulation values in Table 2, as these floors also have the highest impact sound pressure levels. Figure 14 illustrates the linear regression models to show the relationship between the impact sound insulation rating, $L^{'}_{nT,w}$ and perceived annoyance as well as the perceived loudness.

Although the results show 77% correlation between the perceived loudness and $L^{'}_{nT,w}$ values of the floor objects, the correlation between the annoyance and $L^{'}_{nT,w}$ values is only 53%. The $L^{'}_{nT,w}$ rating appears to fail to predict the perceived annoyance in about half of the lightweight floors investigated here. However, this correlation value could be increased to 79.5% by removing the outlier. The outlier datapoint, that is below the regression bounds in both graphs, corresponds to floor M4. This means that for the pre-stressed floor M4, the perceived loudness and annoyance are significantly lower than expected with respect to the calculated impact sound insulation of the floor. This can be explained by the fact that pre-stressing shifts the low-frequency resonances of the floor upwards and damps them to some extent. This improves the low-frequency performance of the floor, and results in a softer and less annoying walking sound. However, pre-stressing does not provide much impact sound insulation at high frequencies. Therefore, $L^{'}_{nT,w}$, which is a measure of impact sound transmission over the frequency range of 100–3150 Hz, does not reflect the improvement in the performance of the pre-stressed floor. Although M4 is an outlier, it is nonetheless a possible floor design. The low correlation between the calculated impact sound insulation and the perceived quality of this floor shows that one should be careful with predicting the floor performance only based on $L^{'}_{nT,w}$ rating.

The correlation between the perceptual attributes and the SNQ rating also decreases after including the adaptation terms, see Table 4.

The p-values in Table 4 show the probability that the results are uncorrelated. The low correlations and the high p-values for the SNQ ratings including the adaptation terms

Table 4. Coefficients of determination of R^2 and statistical significance probability values (p-values).

	Loudness		Annoyance	
	R^2 (%)	p-value	R^2 (%)	p-value
$L'_{nT,w}$	77	0.0003	53	0.009
$L'_{nT,w} + C_{I,50-2500}$	35	0.06	27	0.1
$L'_{nT,w} + C_{I,20-2500}$	39	0.04	45	0.02

could imply that the adaptation terms do not fit with the performance of the presented floors at low frequencies, and thus cannot sufficiently predict the perceived impact sound insulation of these floors. However, the adding of the adaption terms clearly identifies the two floors (M4 and M10) with lowest annoyance. The lack of correlation however needs further investigation.

5 Conclusions

An auralisation tool for investigating the perception of low frequency sound from walkers has been established. The tool consists of measured walking forces, a simplified floor model, and a procedure to map the floor volume velocity due to floor vibrations on a grid of loudspeakers in the ceiling of an especially built living room lab. The approach allows the listener to freely move in the listening room. It also enables the possibility to localise the time varying position of the walker. The validation of the auralisation tool has shown that the position of the loudspeakers with respect to the ceiling in the living room lab is not critical. The procedure of mapping velocity pattern on the floor to a finite number of loudspeakers showed to work well and creates correct spectral contents of the walking sound. It also captures the differences between different floor designs properly. In a pilot study listening tests were carried out using auralized walking sounds for different floor designs. The results showed that 75% of the participants found the plausibility of the auralized walking sounds above the average of the rating range. Familiarity of the test subjects with the impact sound generated by walking is a determining factor which can affect the subject's expectation, and consequently judgement of the sound. Persons with prior familiarity judged the walking sounds as more annoying, more natural and more distinct. The results from the listening tests indicate a correlation between perceived loudness of the walking sounds and annoyance. The prestressed floor M4 was perceived to have the quietest and least annoying walking sound among all the samples. It was also judged to have the least reverberant and thumping sound, which are also parameters connected to perception of annoyance. This design modification can be a potential improvement for lightweight floors, which could be studied further. However, it should be pointed out that prestressing moves the floor resonances to higher frequencies and weakens the impact sound insulation of the floor at those frequencies. On the other hand, the higher frequencies are easier to take care of by e.g. a floating floor design. Although the prestressed floor was subjectively judged to have the best performance among all the tested floor designs, the measured standardized impact sound insulation of the floor did not show any advantage over most of the other floors. It is because the floor M4 is still a lightweight floor and the mobility at frequencies above 120 Hz is in the same order of amplitude as the other floors. Therefore, prestressing does not affect the single number quantity of the standardized impact sound insulation, which is evaluated mainly based on frequencies above 120 Hz. The example also shows the importance of a perceptual evaluation to find adequate solutions which give lower annoyance for the people living in wooden multi-storey houses. In this way the virtual design tool can be very valuable in the design process to evaluate both objective and subjective aspects of the floor design changes.

Conflict of interest

Author declared no conflict of interests.

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